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Deliwala

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(54) **OPTICAL TIME-OF-FLIGHT SYSTEM**

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(51) **Int. Cl.**

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G01S 17/10	(2006.01)
G01S 17/42	(2006.01)
G01S 7/481	(2006.01)

(52) **U.S. Cl.**

CPC ***G01S 3/783*** (2013.01); ***G01S 7/4816*** (2013.01); ***G01S 17/10*** (2013.01); ***G01S 17/42*** (2013.01)

(58) **Field of Classification Search**

CPC H04N 5/21; H04N 9/77; H04N 9/64; G01S 17/89; G01S 17/936

USPC 356/3.01–3.15, 4.01–4.1, 5.01–5.15, 356/6–22, 28, 28.5

See application file for complete search history.

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(57) **ABSTRACT**

Time-of-flight technology may be combined with optical detection technology identifying an angle of a light pulse emitted from a transmitter and reflected off an object based on a proportion of the reflected light pulse detected at each of at least two light sensors. The optical detection technology may include a light detector with two or more light sensors arranged at different orientations with respect to an aperture in the detector so that each sensor is able to detect a different subset of the light passing through the aperture. The effective angle of the light passing through aperture may then be calculated from the proportion of light detected at the each of the sensors. The effective angle information may be combined with a calculated time-of-flight of the light pulse to accurately identify a position of the object relative to the detector in two or three dimensions.

20 Claims, 6 Drawing Sheets

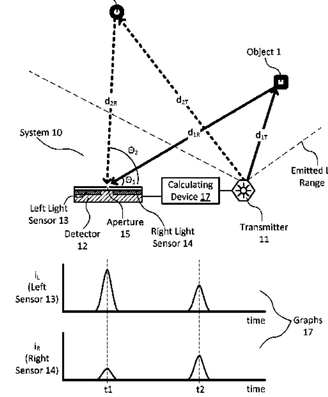


FIG. 1

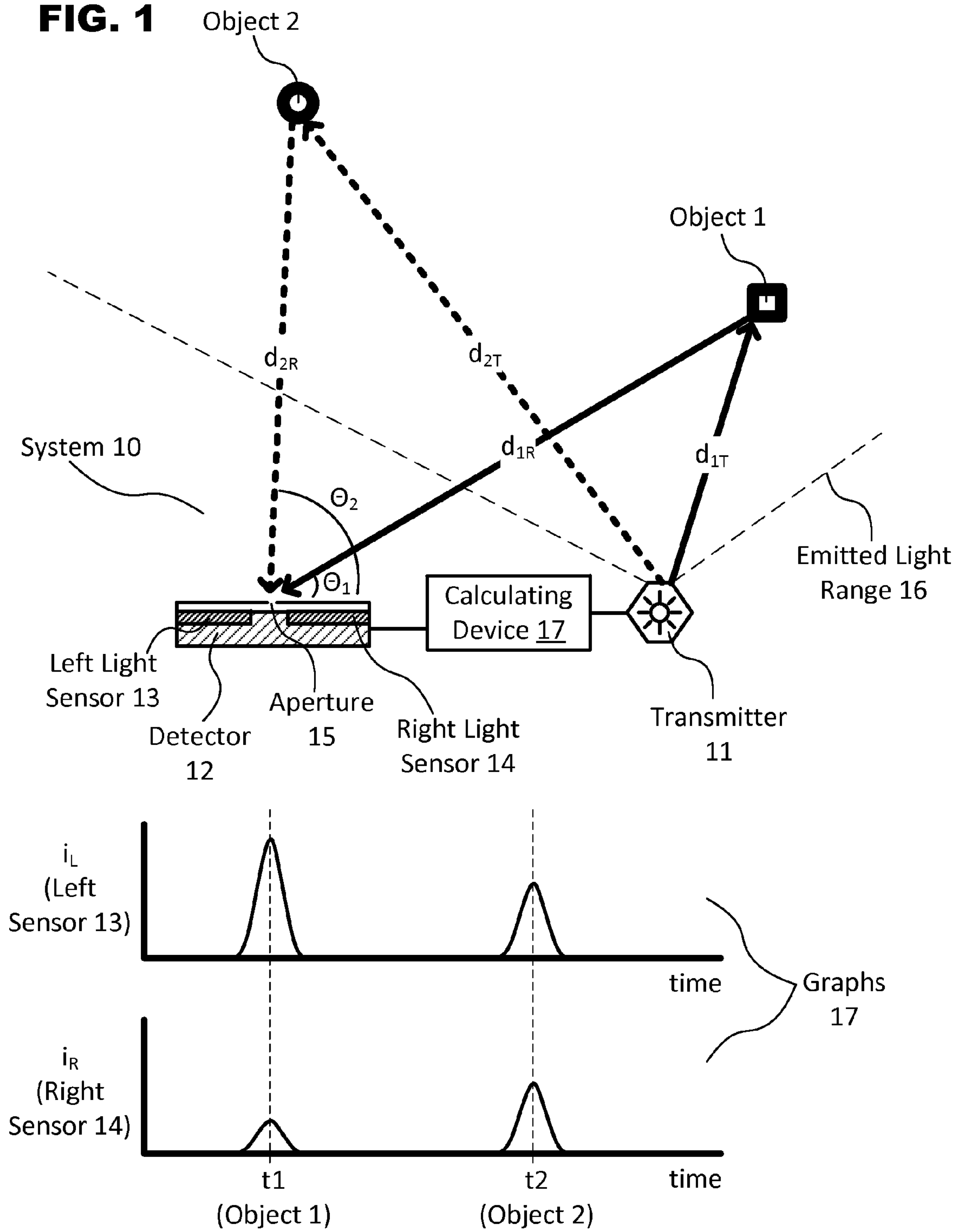

Object 2
Object 1
d_{2R}
d_{2T}
d_{1R}
d_{1T}
System 10
Θ_2
Θ_1
Emitted Light Range 16
Calculating Device 17
Left Light Sensor 13
Detector 12
Aperture 15
Right Light Sensor 14
Transmitter 11
i_L (Left Sensor 13)
time
Graphs 17
i_R (Right Sensor 14)
t1 (Object 1)
t2 (Object 2)
time

FIG. 2

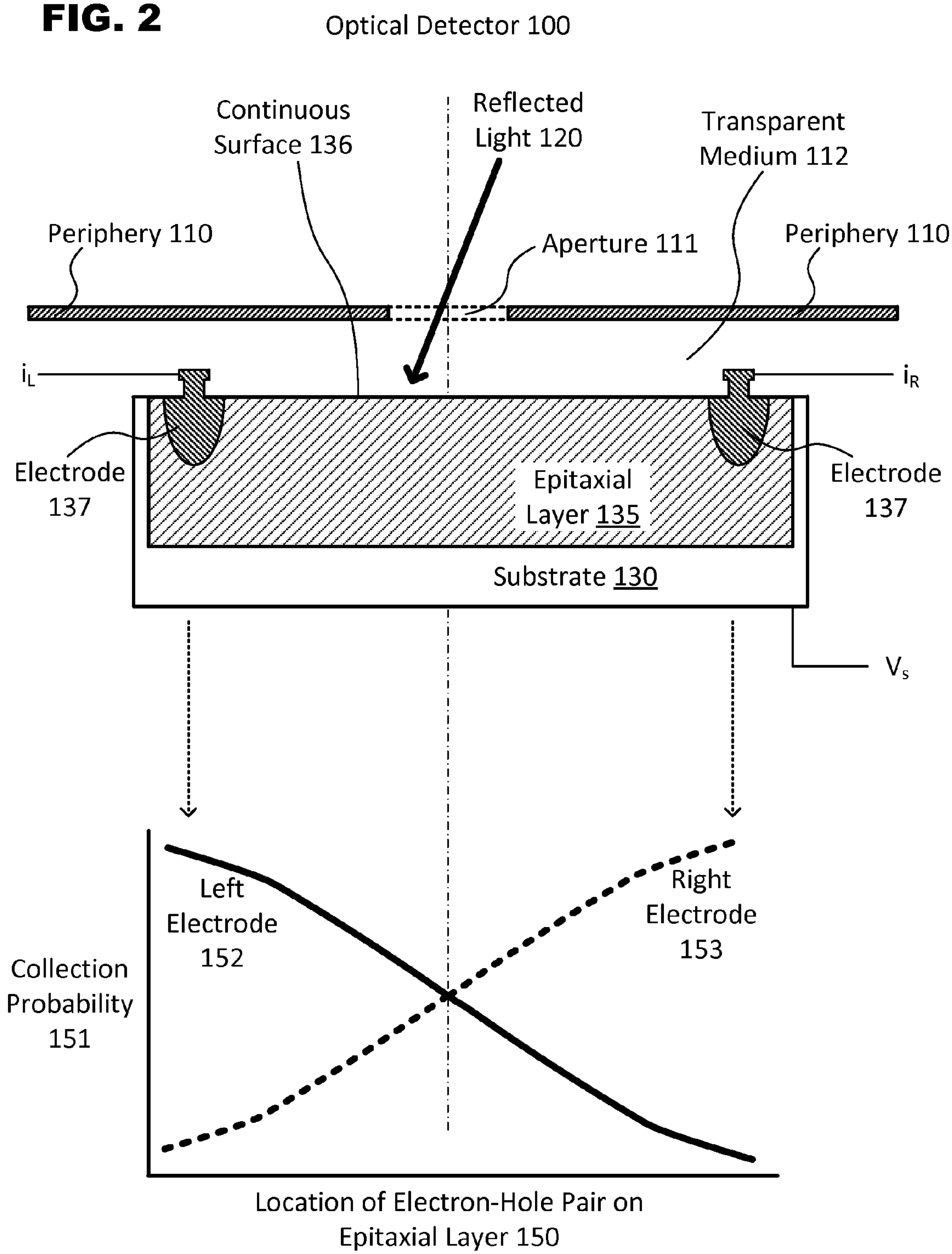

Optical Detector 100
Continuous Surface 136
Reflected Light 120
Transparent Medium 112
Periphery 110
Aperture 111
Periphery 110
i_L
i_R
Electrode 137
Epitaxial Layer 135
Electrode 137
Substrate 130
V_s
Left Electrode 152
Right Electrode 153
Collection Probability 151
Location of Electron-Hole Pair on Epitaxial Layer 150

FIG. 3

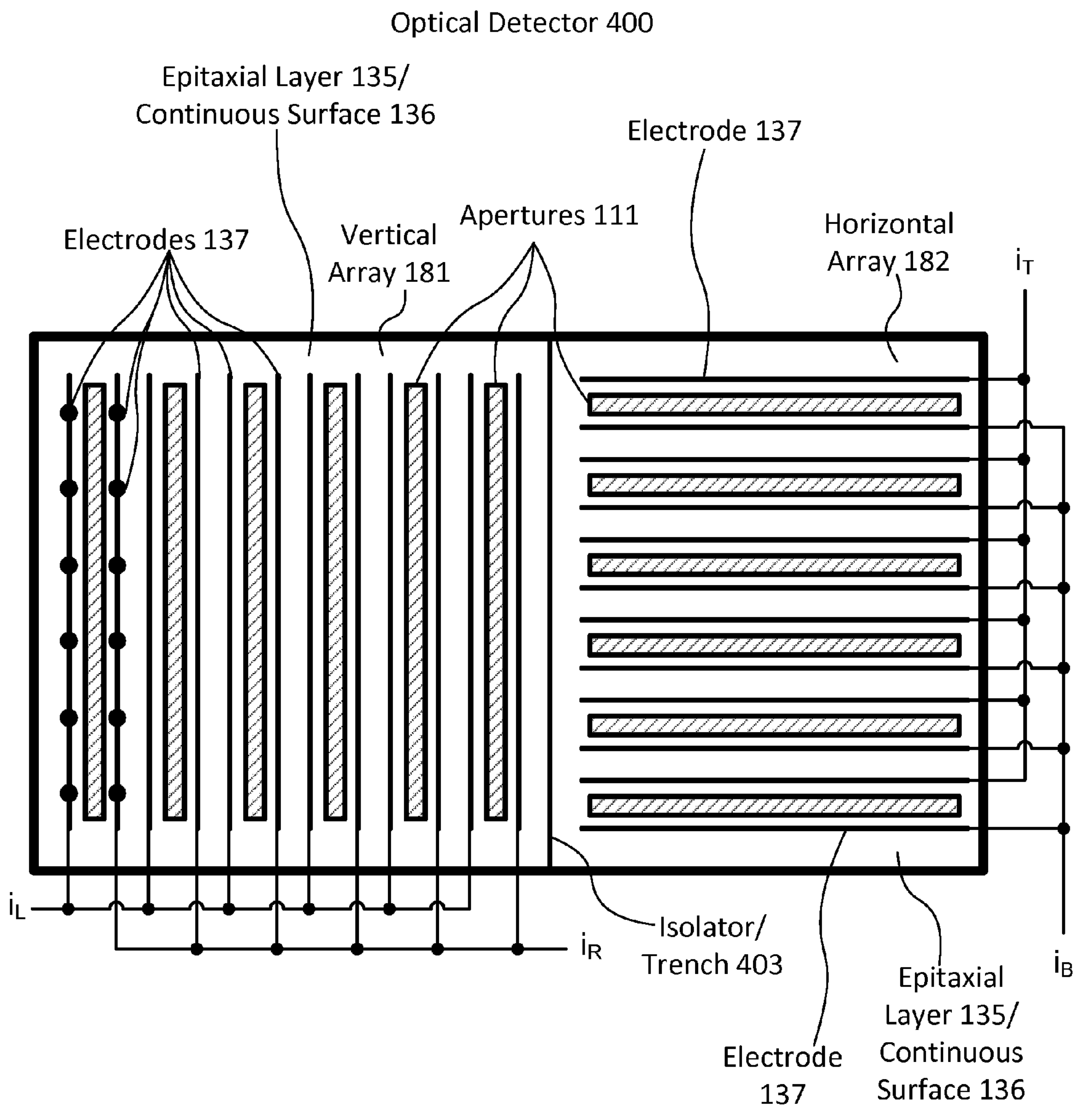

Optical Detector 400
Epitaxial Layer 135/
Continuous Surface 136
Electrode 137
Electrodes 137
Vertical
Array 181
Apertures 111
Horizontal
Array 182
i_T
i_L
i_R
Isolator/
Trench 403
i_B
Epitaxial
Layer 135/
Continuous
Surface 136
Electrode
137

FIG. 4

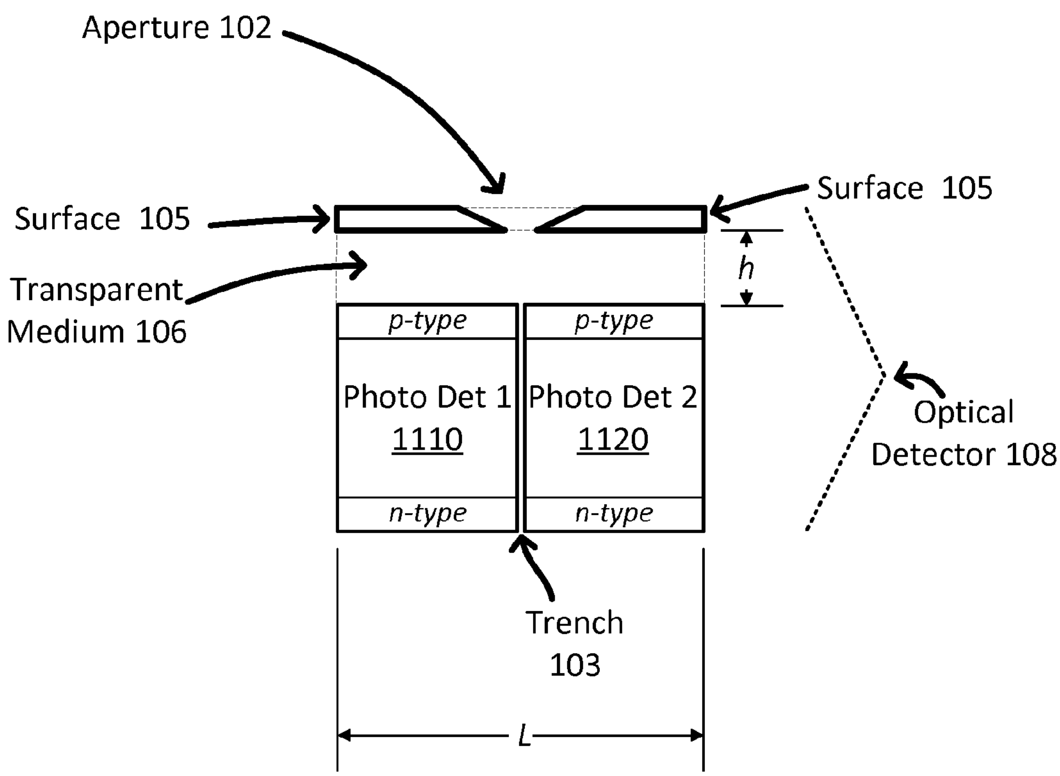
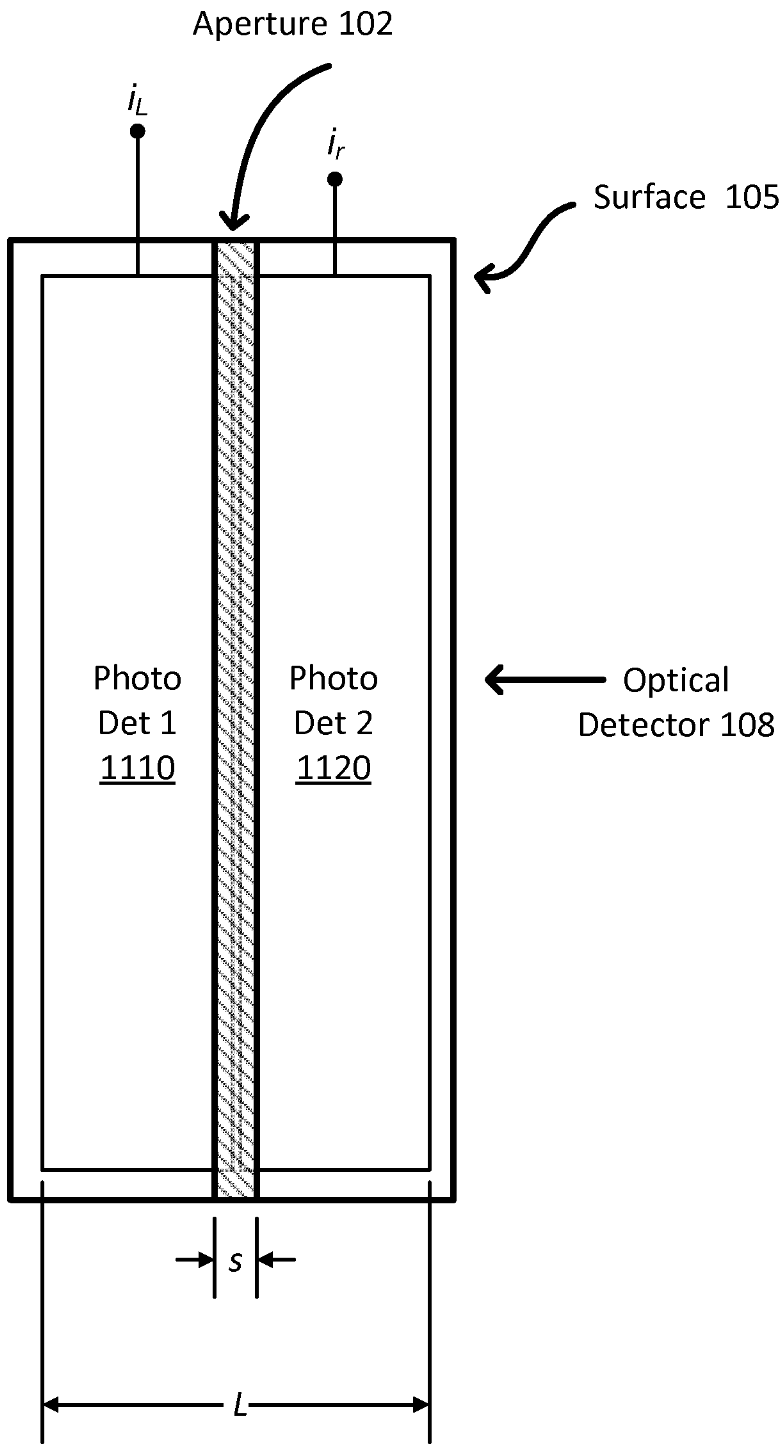
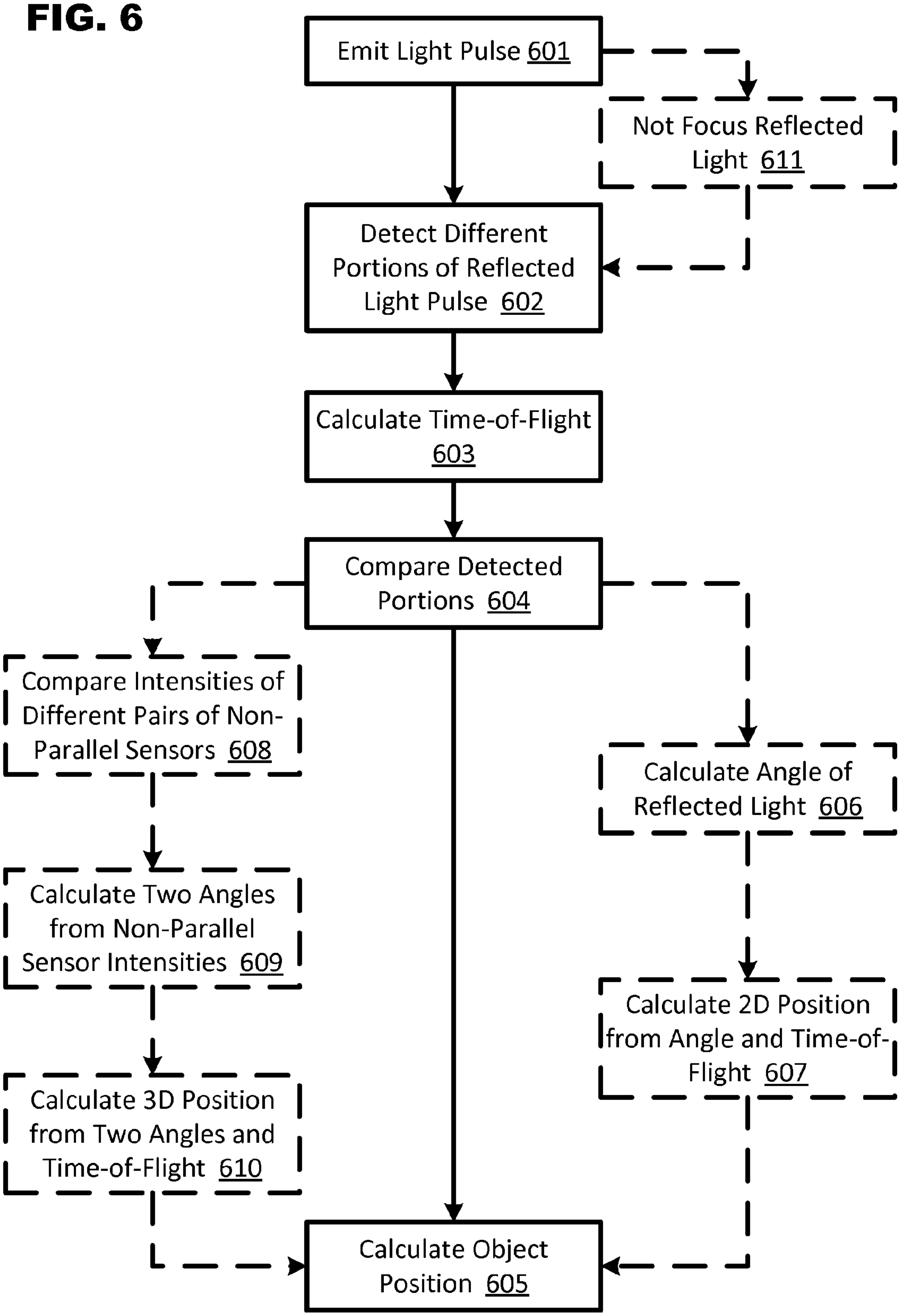

Aperture 102
Surface 105
Surface 105
h
Transparent Medium 106
p-type
p-type
Photo Det 1 1110
Photo Det 2 1120
n-type
n-type
Optical Detector 108
Trench 103
L

FIG. 5



Aperture 102
i_L
i_r
Surface 105
Photo
Det 1
1110
Photo
Det 2
1120
Optical
Detector 108
s
L

FIG. 6


Emit Light Pulse 601
Not Focus Reflected Light 611
Detect Different Portions of Reflected Light Pulse 602
Calculate Time-of-Flight 603
Compare Detected Portions 604
Compare Intensities of Different Pairs of Non-Parallel Sensors 608
Calculate Two Angles from Non-Parallel Sensor Intensities 609
Calculate 3D Position from Two Angles and Time-of-Flight 610
Calculate Angle of Reflected Light 606
Calculate 2D Position from Angle and Time-of-Flight 607
Calculate Object Position 605

OPTICAL TIME-OF-FLIGHT SYSTEM

RELATED APPLICATIONS

This application claims priority to provisional U.S. patent application Ser. No. 61/837,472, filed on Jun. 20, 2013, the content of which is incorporated herein in its entirety.

BACKGROUND

Time-of-flight systems have been used to calculate a distance of an object based on an amount of time it is takes a pulse of light to travel from a transmitters to the object and then from the object to a light detector. Different time-of-flight systems have been used for different applications.

For example, in golf, time-of-flight range finders have been used to calculate a distance to the hole. These range finders have typically been designed as linear systems that output a narrow, straight line laser beam. Once the laser beam struck an object in the straight line path, a reflected portion of the laser beam striking the object was detected at a detector and the distance of the object was calculated. These range finders could only measure the distance of the first object in the laser beam path; the range finders could not differentiate between different objects at different distances nor could they identify the distance of objects in more than one dimension.

More sophisticated time-of-flight devices included image sensors, such as those in digital cameras, containing an array of many light detection cavities or photosites. The image sensors were capable of measuring the distance and position of multiple objects in at least two dimensions based on the detected location of the light reflected off each object within the array and the calculated time-of-flight. However, image sensors are expensive and slow. Image sensors require relatively long processing times to analyze the data at each of the photosites in the array. Additionally, while the accuracy of these devices improves as the number of photosites increases, the cost and processing time need to analyze the data at each of the photosites also increases. This makes the use of image sensors impractical for low cost or time sensitive applications, such as vehicle crash avoidance systems.

There is therefore a need for quickly and accurately calculating a position of multiple objects in at least two dimensions in a cost effective manner.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows an exemplary time-of-flight system and plots of light sensor currents.

FIG. **2** shows a first exemplary optical detector in an exemplary time-of-flight system.

FIG. **3** shows a second exemplary optical detector in an exemplary time-of-flight system.

FIG. **4** shows an exemplary side-view perspective of a third exemplary optical detector in an exemplary time-of-flight system.

FIG. **5** shows an exemplary top-view perspective of the third exemplary optical detector shown in FIG. **4**.

FIG. **6** shows exemplary methods.

DETAILED DESCRIPTION

In different embodiments, time-of-flight technology may be combined with optical detection technology identifying an angle of detected light based on a proportion of the light detected at each of at least two light sensors. The optical detection technology may include a light detector with two or more light sensors. The light detector may have an outer surface or periphery with an aperture. Each of the light sensors may be arranged at different orientations in the light detector with respect to the aperture so that each sensor is able to detect a different subset of the light passing through the aperture. The subset of the light detected at each light sensor may change as the angle of the light passing through the aperture changes. The effective angle of the light passing through aperture may then be calculated from the proportion of light detected at the each of the sensors associated with the aperture.

The time-of-flight technology may include a transmitter emitting a pulse of light at a predetermined time, the above mentioned light detector, and a calculation device. The light detector may be configured to detect the emitting light pulse. In some instances the transmitter and/or light detector may be modulated to improve the detection accuracy at the light detector. The calculation device may calculate a time-of-flight of the emitted light pulse based on a time difference between a time the light pulse is emitted and a time the light pulse is detected at the light detector. This time difference may represent the time needed for the light pulse to travel first from the transmitter to an object in the path of light pulse and second from the object to the light detector after the light pulse strikes the object and is reflected off the object. The distance that the light pulse traveled may be calculated by multiplying the calculated time-of-flight by the speed of light.

The distance that the light pulse traveled calculated using the time-of-flight technology may be combined with the effective angle of the light passing through the aperture calculated using the light detection technology to provide a position of the object relative to the detector in two dimensions with a minimum of two light sensors in the optical detector. The position of the object relative to the detector may also be calculated in three dimensions with a minimum of three light sensors in the optical detector.

Multiple objects in the path of the light pulse may also be identified and their respective positions may also be calculated. In instances with multiple objects located at different distances from the transmitter and the light detector, the time needed for the light pulse to travel from the transmitter to the object and then to the detector may vary. As a result, the light detector may first detect the received light pulse after it is reflected off a first object located closest to the transmitter and the detector. Thereafter, the light detector may again detect the light pulse a short time later after it is reflected off a second object located further away than the first object. The proportion of the reflected light reaching each of the light sensors may vary each time the light pulse is detected due to the different locations of the objects relative to each other and then the detector.

As discussed herein, object position information of one or multiple objects may be determined in two or three dimensions by combining the output from a respective minimum of two or three light sensors in a light detector with the calculated time-of-flight information. By using substantially less light sensors than a traditional digital camera image sensor, positional information of one or more objects may be calculated quickly and accurately in at least two dimensions at a much lower cost.

FIG. **1** shows an exemplary time-of-flight system **10** and plots **17** of currents i_L and i_R from a respective left sensor **13** and right sensor **14**. An exemplary time-of-flight system **10** may include a transmitter **11**, a light detector **12**, and a calculation device **17** coupled to the transmitter **11** and the light detector **12**.

The transmitter **11** may emit a pulse of light. The light pulse may be emitted over a range **16**. The range **16** may include a predetermined volume of space extending from the transmitter **111**. The emitted light may reach any object within the range **16**. The example shown in FIG. **1** includes two objects **1** and **2** with the range **16** of the transmitter **11**. Object **1** is located a distance d_{1T} from the transmitter **11** and a distance d_{1R} from a center of an aperture **15** in the detector **12**. Object **2** is located a distance d_{2T} from the transmitter **11** and a distance d_{2R} from the center of the aperture **15**.

Light emitted from the transmitter **11** may have to travel distances d_{1T} and d_{2T} to reach respective objects **1** and **2**. Once the emitted light reaches these objects **1** and **2**, a portion of the light may be reflected off the respective objects **1** and **2** and then travel respective distances d_{1R} and d_{2R} to reach the detector **12**. The portion of the light pulse reflected off object **1** that reaches the detector **12** may have an angle of θ**1** with respect to the detector **12**. The portion of the light pulse reflected off object **2** that reaches the detector may have an angle of θ**2** with respect to the detector **12**.

The detector **12** in FIG. **1** includes two light sensors, a left sensor **13** and a right sensor **14** within a housing having an aperture **15**. The light sensors **13** and **14** may in some instances include photodetectors or electrodes connected to an epitaxial layer on a substrate. Each of the light sensors **13** and **14** may generate a respective current proportional to amount of light at the respective sensor **13** and **14**.

The sensors **13** and **14** may be coupled to a calculation device **17**. The transmitter **11** may also be coupled to the calculation device **17**. The calculation device **17** may include a central processing unit, microcontroller, or other processing device capable of performing mathematical operations. The calculation device **17** may be configured to calculate a time-of-flight of the light pulse based on the time difference between a start time of the emission of the light pulse at the transmitter **11** and a detection time of the light pulse at the detector **12**.

The calculated time-of-flight t**1** and t**2** of the light pulse with respect to each object **1** and **2** may then be multiplied by the speed of light to determine the total distance traveled by the light. This distance information may be used to determine a position of the object in one dimension relative to the detector. The total distance traveled by the light with respect to each object may be calculated as:

$$d_{1T}+d_{1R}=c\cdot t1 \tag{1}$$

$$d_{2T}+d_{2R}=c\cdot t2 \tag{2}$$

In those instances where the distance between transmitter **11** and the detector **12** is much less than the distance between the detector **12** and the respective object **1** or **2**, the distance d_{1T} and d_{1R} may be approximated as being equal to each other and the distances d_{2T} and d_{2R} may also be approximated as being equal to each other. Thus, equations (1) and (2) may be simplified to:

$$d_{1R}\approx(c\cdot t1)/2 \tag{3}$$

$$d_{2R}\approx(c\cdot t2)/2 \tag{4}$$

The calculation device **17** may also compare the currents i_L and i_R outputted by each respective sensor **13** and **14** to determine a proportion of the total current outputted by each sensor **13** and **14**. The proportion of the currents outputted by each sensor may be used to determine the angle of reflected light with respect to the detector **12**. For example, as shown in FIG. **1**, the light reflected off object **1** may arrive at the aperture **15** of the detector at an angle θ**1**. At this angle θ**1**, most of the reflected light will be directed onto the left light sensor **13** instead of the right light sensor **14**. As a result, the left sensor **13** may output a substantially higher current than the right sensor **14**.

However, the light reflected off object **2**, which is located nearly vertical to the aperture **15** may arrive at the aperture **15** at a near vertical angle θ**2**. Thus, the reflected light off object **2** may be more evenly distributed between the left sensor **13** and the right sensor **14**. As a result, the currents generated by the left sensor **13** and the right sensor **14** may be very similar. Thus, the angle of the reflected light may be calculated based on the ratio of currents detected by each of the sensors **13** and **14**. This angle information may provide information about the location of the object in one dimension.

The two graphs **17** show relative changes to the current i_L at the left sensor **13** (upper graph) and the current i_R at the right sensor **14** (lower graph) over time. The pulse may be emitted from the transmitter **11** at time t**0**. At about time t**1**, the portion of the light pulse reflected off object **1** may be received at sensors **13** and **14**. This may cause the respective current spikes at time t**1** depicted in both graphs. Due to the location of object **1** relative to the aperture **15**, a greater proportion of the reflected light may project onto the left sensor **13** instead of the right sensor **14**. Since the current generated at each sensor **13** and **14** may be proportional to the amount of light projecting onto the sensor, the current i_L generated at the left sensor **13** may be substantially more than the current i_R at the right sensor **14** when the sensors **13** are spaced equidistant from the aperture **15** and the aperture **15** is symmetric.

At about time t**2**, the portion of the light pulse reflected off object **2** may be received at sensors **13** and **14**. This may cause the respective current spikes at time t**2** depicted in both graphs. Due to the nearly vertical location of object **2** above the aperture **15**, a roughly equal proportion of the reflected light may project onto each of the sensors **13** and **14** when the sensors **13** are spaced equidistant from the aperture **15** and the aperture **15** is symmetric. Since the current generated at each sensor **13** and **14** may be proportional to the amount of light projecting onto the sensor, the current i_L generated at the left sensor **13** may be relatively similar to the current i_R at the right sensor **14**.

The angles θ**1** and θ**2** calculated by the calculation device **17** may be similar to:

$$\theta1\sim i_{L_{t1}}/i_{R_{t1}} \tag{5}$$

$$\theta2\sim i_{L_{t2}}/i_{R_{t2}} \tag{6}$$

In some instances, the detector **12** may have two or more light sensors. Each of the light sensors may detect a different portion of the light pulse emitted from the transmitter **11** and reflected off an object. A calculation device **17** may be coupled to the transmitter **11** and the detector **12**. The calculation device **17** may calculate a time-of-flight of the light pulse and a position of the object relative to the detector **12** based on the calculated time-of-flight and a calculated proportion of the portions of reflected light pulse detected at the light sensors.

If there are multiple objects in a range **16** of the emitted light pulse, then each of the light sensors may detect a different portion of the light pulse reflected off each of the multiple objects. The calculation device **17** may calculate a time-of-flight of the light pulse with respect to each of the objects based on peak currents generated at each light source over time. The calculation device **17** may also compare the respective peak currents of different light sources to each other and the calculated time-of-flight for the respective object to calculate the position of the respective object.

When the detector **12** includes two light sensors, the calculation device **17** may calculate the object position in two dimensions. A first of the two dimensions may be obtained from the calculated proportion of the portions of the reflected light pulse detected at the light sensors. A second of the two dimensions may be obtained from the calculated time-of-flight.

FIG. **2** shows an exemplary optical detector **100**. The optical detector **100** may include a periphery **110** such as an exterior surface or housing. In those instances where the optical detector **110** is formed from a semiconductor, the periphery **110** may be an outer surface of the semiconductor. In those instances where the optical detector **110** is formed as an integrated circuit, the periphery **110** may be an exterior surface of the integrated circuit. The periphery **110** may be metallic or made from another substance impervious to light.

The periphery **110** may have an aperture **111** that allow reflected light **120** from the light pulse emitted by the transmitter and reflected off an object to pass through the aperture **111**. The aperture **111** may be any type of opening in or section of the periphery **110** that is transparent. In some instances, the aperture **111** may be a physical opening or hole in the periphery **110**. In other instances, the aperture **111** may be section of the periphery **110** that is altered to make it transparent or permeable to light without necessarily creating a physical opening or hole. Such an altering may occur in some instances by removing an opaque coating covering a section of the periphery **110** to make it transparent, replacing a section of the periphery **110** with a transparent material, or by other techniques. The aperture **111** may be a slit or pinhole, or it may have any other shape or form.

One or more edges of aperture **111** may be beveled. In some instance, each edge of the aperture directed away from the epitaxial layer **135** may be beveled to reduce an amount of incident light that is reflected off the edge and redirected onto the epitaxial layer **135**.

An interior of the optical detector **100** may include a substrate **130** having an epitaxial layer **135**. The epitaxial layer **135** may be applied on a surface of the substrate **130** facing the aperture **110**. The epitaxial layer **135** may, in some instances, be a germanium based, silicon based, or germanium and silicon based epitaxial layer. Other types of epitaxial layers may be used in other embodiments.

Two or more electrodes **137** may be situated at least partially in or on the epitaxial layer **135** so as to electrically contact the epitaxial layer. The contacting of the electrodes **137** to the epitaxial layer **135** may enable electrodes **137** to collect electron-hole pairs in the epitaxial layer **135** generated from the absorption of the reflected light **120** in the epitaxial layer **135** to detect a quantity of the light received at the epitaxial layer **135**. The depths that the electrodes **137** are positioned in the epitaxial layer **135** may be selected to correspond to an expected penetration depth of a wavelength of the reflected light **120** to be detected to maximize the collection of electron-hole pairs by the electrode at that penetration depth.

The electrodes **137** may have any shape. For example, in some instances the electrodes may be discrete, point shaped electrodes. In other instances the electrodes may be continuous electrodes having a length or other dimension corresponding to that of the aperture **111**, such a length corresponding to a slit length of a slit aperture or a rectangular shape corresponding to a rectangularly shaped slit aperture.

The two or more electrodes **137** may be located at predetermined positions relative to the aperture **111**. For example, in some instances, such as that shown in FIG. **1**, the electrodes **137** may be located at equal distances from a center of the aperture **111**. In other instances, one or more of the electrodes **137** may be located at different distances than other electrodes **137** from the center of the aperture **111**. Electrodes **137** may also be located opposite from each other relative to the center of the aperture **111** in some instances, but in other instances, the electrodes **137** may be positioned in different orientations.

The epitaxial layer **135** may also be continuous and have a continuous surface **136** between each of the electrodes. This continuity ensures that the entire section of the epitaxial layer located between the electrodes **137** is available to absorb light and generate electron-hole pairs. In the past, the presence of trenches and other isolators compartmentalizing the epitaxial layer **135** prevented maximum absorption of incident light reaching the epitaxial layer **135** and generation of electron-hole pairs collected by the electrodes.

The electrodes **137** may be electrically coupled to one or more current sensing devices that is able to identify a relative amount of collected electron-hole pairs at each electrode **137** that were generated in the epitaxial layer **135** by the absorption of the reflected light **120** in the epitaxial layer **135**. The graph **150-153** shown in FIG. **1** depicts a probability distribution function of a probability **151** that electron-hole pairs generated at different locations in the epitaxial layer **135** along the axis **150** will be collected by either the electrode **137** on the left side **152** of FIG. **1** (as indicated by the solid plot line) or the electrode **137** on the right side **153** of FIG. **1** (as indicated by the dashed plot line). Based on this known probability distribution, the measured currents at the respective left **152** and right **153** electrodes **137** (i_L and i_R) may be compared to calculate an expected centroid of the reflected light **120** between the electrodes **137**. An angle of the reflected light **120** may then be calculated based on the expected centroid. The probably distribution function may be determined experimentally. This approach of using the probability distribution function to calculate the angle of the reflected light **120** may be accurate over only small separation distances between the electrodes **137** on the order of tens of microns rather than the several millimeters needed to build a traditional angle measuring photodiode detector. In instances where a millimeter scale photodetector is needed, several optical detectors **100** may be coupled together to achieve the millimeter scale.

An angle of the reflected light **120** passing through the aperture **111** and reaching the epitaxial layer **135** may be calculated from the current measured at each of the electrodes **137**. In the case of two electrodes **137** as shown in FIG. **1**, the angle θ of the reflected light **120** may be calculated from the left and right currents i_L and i_R as:

$$f(\theta) = \frac{i_L - i_R}{i_L + i_R} \tag{1}$$

The continuous nature of the epitaxial layer **135** between the electrodes **137** may cause in a resistance between each of the electrodes **137** equivalent to an effective resistor R_{eff} between the electrodes. The actual size of R_{eff} may vary depending on the distance between the electrodes, the number of electrodes, the resistivity of the epitaxial layer **135**, the thickness of the epitaxial layer **135**, and a bias voltage V_S applied to the substrate. A voltage source applying bias voltage V_S may be coupled to substrate and may apply the bias voltage to the epitaxial layer **135** to change a light detection sensitivity of the electrodes **137** by altering the amount of light required to be absorbed in the epitaxial layer **135** to generate an electron-hole pair. The optical detector **100** may be designed to have a large R_{eff} to suppress noise between circuits connected to each of the electrodes and to reduce Johnson noise. R_{eff} may be made large by creating a substantial depletion region in the epitaxial layer **135** around the electrodes **137**. This may be accomplished using a slightly n-type high resistivity epitaxial layer **135** with p-type electrodes to ensure a substantial depletion region around the electrodes. In other instances a p-type epitaxial layer **135** may be used with n-type electrodes.

In some instances, the aperture **111** and/or periphery **110** may be positioned directly on top of the epitaxial layer **135**. In other instances, the epitaxial layer **135** may be separated from the aperture **111** and/or periphery **110** by a transparent medium **112**. The transparent medium **112** may be a solid, liquid, or gas that is transparent and may include substances such as air, polymers, and glass. In some instances where the epitaxial layer **135** is separated from the aperture **111** and/or periphery **110**, the periphery **110** and/or aperture **111** may be positioned at various heights above the epitaxial layer **135**, including but not limited to heights less than 30 microns and/or heights less than 10 microns.

The optical detector **100** need not include any lens or other devices that focus light. Thus, the aperture **111** and medium **112** need not focus the reflected light **120** passing through them. By not including any lenses or other light focusing devices, it is possible to reduce the size and manufacturing costs and manufacturing time of the optical detector **100**. The light detection efficiency of the optical detector **100** may, in some instance, be improved by using one or more lens to focus light on or below the continuous surface **136** of the epitaxial layer **135**. In some instances the aperture may be replaced with a lens.

FIG. **3** shows an embodiment of an optical detector **400** including both a vertical array **181** and a horizontal array **182** of slit apertures **111** and corresponding sets of electrodes **137**. FIG. **3** shows six exemplary vertical slit apertures in the vertical array **181** and six exemplary horizontal slit apertures in the horizontal array **182**. Each of the slit apertures **111** may have a set of one or more electrodes positioned parallel to the slit aperture **111** along a longitudinal direction of the slit aperture **111** on both sides of the slit aperture **111**. The slit apertures **111** may also have beveled edges pointing away from the epitaxial layer **135** to minimize the likelihood that the reflected light **120** will be reflected off the edge and redirected onto the epitaxial layer **135**. Each electrode **137** may be arranged in the epitaxial layer **135** to detect a respective quantity of the incident light passing through each aperture.

Some of the electrodes **137** may be rectangularly shaped and extend longitudinally for at least a similar distance as the respective slit aperture **111** associated with the electrode **137**. Some of the electrodes **137** may also be positioned parallel to its associated slit aperture **111**, and in some instances, pairs of these electrodes **137** may be positioned at equal distances from and on either side of the associated slit aperture **111** as shown in FIG. **3**. Each pair of these electrodes **137** may also be centered with a center of its corresponding slit aperture **111**. In other instances, one or more electrodes or electrodes pairs may be offset from a center of its corresponding slit aperture **111**.

In some instances, the electrodes **137** may include several point electrodes such as those shown parallel to both longitudinal sides of the left most aperture **111** in FIG. **3**. The point electrodes may be positioned along two or more imaginary lines oriented parallel to the slit aperture. In the example shown in FIG. **3**, the two imaginary lines may run vertically along both sides of the left most slit aperture **111**. Respective point electrodes running along each imaginary line associated with a particular aperture may be electrically coupled together.

The vertical slit apertures **111** in the vertical array **181** may be arranged parallel to each other and perpendicular to the horizontal slit apertures **111** in the horizontal array **182**. Different electrodes **137** associated with different apertures **111** may be coupled together provided that the orientation of the electrode **137** with respect to its corresponding aperture **111** is similar. For example, as shown in FIG. **3**, all of the electrodes located on the left side of different apertures **111** may be electrically coupled to generate an aggregated left current i_L and increase the light detection efficiency of the optical detector **400**. Similarly, all the electrodes on the right side, top side, and bottom side of the apertures **111** may also be coupled together to generate aggregate right i_R, top i_T, and bottom i_B currents and further increase the light detection efficiency.

In some instances, an electrical signal isolator **403** may be inserted or formed in the epitaxial layer **135** to subdivide the epitaxial layer **135** into multiple separate continuous surfaces **136**. The isolator **403** may surround one or more electrodes **137** to isolate the ability of the electrodes **137** to collect only those electron-hole pairs that are generated within the isolated region surrounding the electrode **137**. In some instances the isolator **403** may be used to compartmentalize the epitaxial layer **135** around each set of electrodes associated with each aperture **111** so that the quality of light reaching the epitaxial layer **135** that is detectable by a respective electrode **137** is isolated to only the reflected light **120** that actually passes through the aperture **111** associated with the electrode **137**. In the example shown in FIG. **3**, the isolator **403** is a trench that subdivides the epitaxial layer **135** into two continuous sections, a first section encompasses the electrodes **137** in the vertical array **181** and a second section encompasses the electrodes **137** in the horizontal array **182**.

An optical detector similar to that shown in FIG. **3** may include a periphery **110** having multiple slit apertures **111**. At least two of the slit apertures **111** may be oriented orthogonally to each other. The optical detector may also include a substrate **130** having an epitaxial layer **135** receiving light **120** passing through each of the slit apertures **111**. The optical detector may also include a set of electrodes **137** associated with each slit aperture **111**. Each electrode **137** in each set may be arranged in the epitaxial layer **135** to detect a quantity of the received reflected light **120** passing through the respective slit aperture **111**. The epitaxial layer **135** may have a continuous surface **136** at least for each set of electrodes **137** that encompasses the electrodes **137** in each respective set of electrodes **137**. In some instances the epitaxial layer **135** may have a single continuous surface **136** encompassing every electrode **137**. The epitaxial layer **135** may be germanium based in some instances.

The optical detector **400** shown in FIG. **3** includes more than three light sensors. The currents generated at each of these light sensors in both the vertical array **181** and the horizontal array **182** may be used by a calculation device to calculate the position of an object in three dimensions. Two of the dimensions of the position of the object may be obtained from the calculated proportion of the portions of the reflected light pulse detected at the light sensor electrodes **137** in both the vertical array **181** and the horizontal array **182**. The third dimension position information may be derived from the calculated time-of-flight of the light pulse.

FIG. **4** shows an exemplary side-view perspective and FIG. **5** shows an exemplary top-view perspective of an optical detector **108** having a single aperture **102** and an associated pair of photodetectors **1110** and **1120** in an embodiment of the invention. In these embodiments, the emitted light pulse that is reflected off an object positioned on one side of an optical detector surface **105** may pass through the aperture **102** to reach the photodetectors **1110** and **1120**. In different embodiments, different numbers of apertures and photodetectors may be used.

The aperture **102** may be a slit having a width sand may be positioned at a height h above the photodetectors **1110** and **1120**. In some configurations, h may be less than 30 μm and in some space saving configurations, h may be less than 10 μm or even less than 1 μm. A medium allowing light to pass through it may be placed between the aperture **102** and the photodetectors **1110** and **1120**. In some instances, the medium may be glass, including forms of glass used during semiconductor device fabrication. The width s of the photodetector **1110** and **1120** may depend on an angular range requirement and h.

The angle of the light reflected off an object may be calculated by measuring a relative proportion of photocurrents detected at each of the photodetectors, provided that the reflected light is able to reach at least two of the photodetectors. When all of the reflected light from the light source falls on only one detector it may not be possible to measure changes to the angle of the reflected light. The maximum angle θ_{max} that may be measured may occur approximately at $\tan(\theta_{max})\sim\pm s/h$.

If the reflected light is angularly distributed so that the reflected light reaches the photodetectors from multiple angles with intensity $\mathrm{In}(\theta)$, then the average angular position of the emitted light may be calculated. Assuming $S_L(\theta)$ and $S_r(\theta)$ are the respective responses of the left and right photodetectors to light at angle θ detected at the photodetectors, then the photocurrents measured by the left and rights photodetectors may calculated as:

$$i_L = \int_\theta \mathrm{ln}(\theta)\cdot S_L(\theta)\,d\theta \text{ and } i_r = \int_\theta \mathrm{ln}(\theta)\cdot S_r(\theta)\,d\theta.$$

However, the photocurrents calculated from both of these integrals may be equivalent to photocurrents generated from a "virtual" point light source at a centroid angle of the distribution. This centroid angle may be calculated from the measured photocurrents at the left and right photodetectors and used to calculate the equivalent centroid angle of the light source.

The photodetector pair **1110** and **1120** may have a combined total width L, the center of which may be aligned with a center of each respective aperture **102**. In some embodiments, a center of a photodetector pair may be offset from the center of a respective aperture and in some other instances the amount of offset may vary for different photodetector pairs. Optical detector **108** may be configured so that the outputs of corresponding photodetectors in each of a plurality of photodetector pairs are coupled together to increase light collection efficiency. For example, the photocurrent outputs of the left most photodetector **1110** in each of several photodetector pairs may be coupled together to generate an aggregate current i_L proportional to an aggregated detected amount of light at each of the left most photodetectors **1110**. Similarly, the photocurrent outputs of each of the right most photodetectors **1120** in each of several photodetector pairs may be coupled together to generate an aggregate current i_r of the right most photodetector **1120**.

The optical detector surface **105** may be metallic in some instances, such as a metal interconnecting layer used in silicon integrated circuit manufacturing. The edges of the apertures **102** may be beveled, as shown in FIG. **4**, and in some instances the beveled edges may be pointed away from the detectors, as also shown in FIG. **4**. Each of the photodetectors **1110** to **1120** may be electrically isolated and separated from the others by a trench **103**.

As the angle and direction of the reflected light changes from the left side of FIG. **4** above the surface **105** to the right side above the surface **105** (or vice versa), the projection of the reflected light through the aperture **102** may also change from initially being entirely projected onto the right detector **1120**, to being projected less on the right detector **1120** and more on the left detector **1110** until the reflected light is projected entirely on the left detector **1110**.

The angle of the reflected light may be calculated by comparing the photocurrents i_L and i_r, which may be proportional to the detected light at the left and the right photodiodes respectively after the reflected light passes through the aperture **102**. The ability to calculate the angle of the reflected light may be dependent on the ability to detect the reflected light at each photodetector **1110** and **1120** as the angle calculation depends on the proportion of light reaching each of the photodetectors **1110** and **1120**.

FIG. **6** shows exemplary methods. In box **601**, a light pulse may be emitted. The light pulse may be emitted from a transmitter at a predetermined emission time. The transmitted may be coupled to a calculation device that is configured to calculate a time-of-flight of the light pulse starting from the predetermined emission time until a reflected portion of the light pulse is subsequently detected at a detector.

In box **602**, different portions of the light pulse may be detected at each of a plurality of light sensors in the detector after the light pulse is reflected off an object and passes through an aperture.

In box **603**, a time-of-flight of the light pulse may be calculated based on an elapsed travel time of the light pulse starting from the time the light pulse is emitted from the transmitter until the reflected portion of the light pulse is detected at the detector.

In box **604**, an intensity of at least two of the different portions of the reflected light pulse detected at two or more of the light sensors in the detector may be compared to each other. In some instances, this comparing may include calculating a ratio or proportion of the total light detected at each of the respective at least two light sensors.

In box **605**, a position of the object may be calculated based on the calculated time-of-flight in box **603** and the intensity comparing in box **604**.

In box **606**, an angle of the reflected light pulse relative to the light sensors and/or the detector may be calculated from the intensity comparing in box **604**.

In box **607**, a two-dimensional position of the object relative to the light sensors and/or the detector may be calculated. A first dimension of the two-dimensional position of the object may be calculated based on the angle calculated in box **606**. A second dimension of the two-dimensional position of the object may be calculated based on the time-of-flight calculated in box **603**.

In some instances, a light detector may include three or more light sensors at least two of which are oriented non-parallel to each other. The non-parallel orientation of these light sensors may be used to determine at least two different angles of the reflected light with respect to the detector. Two different angles may be used to calculate a position of the object in two dimensions. In box **608**, the intensity of different portions of the light pulse detected at each of a first pair of light sensors may be compared to each other and the intensity of different portions of the light pulse detected at each of a second pair of light sensors may also be compared to each other. The second pair of light sensors may be oriented non-parallel to the first pair of light sensors in the detector.

In box **609**, a first angle of the reflected light pulse with respect to the first pair of light sensors may be calculated from the first light sensor pair intensity comparing and a second angle of the reflected light pulse with respect to the second pair of light sensors may be calculated from the second pair intensity comparing.

In box **610**, a three-dimensional position of the object relative to the detector and/or the light sensors may be calculated. The first and second dimensions of the three-dimensional position may be calculated based on the first and second angles of the reflected light pulse calculated in box **609**. The third dimension of the three-dimensional position may be calculated based on the time-of-flight calculated in box **603**.

In box **611**, at least the portions of the light pulse reflected off an object need not be focused before performing the functions in boxes **602** to **610**.

In some instances, the detector may be configured to detect the intensity of different portions of the reflected light pulse passing through an aperture in a periphery of the detector. The intensity of the different portions of the reflected light pulse may be detected at each of a plurality of electrodes in an epitaxial layer on a substrate within the detector. The epitaxial layer may have a continuous surface encompassing each of the electrodes. The surface of the substrate contain the epitaxial layer may face the aperture in the periphery of the detector so that the reflected light passing through the aperture reaches and is absorbed in the epitaxial layer. The detected intensities of the light pulse at two or more of the electrodes may be compared to each other and the position of the object may be calculated based on the calculated time-of-flight and the compared intensities.

In other instances, the detector may be configured to detect the intensity of different portions the light pulse at each of a plurality of photodetectors after the reflected light pulse passes through an aperture in the detector. The detected intensities of the light pulse at two or more of the photodetectors may then be compared to each other and the position of the object relative to the detector may be calculated based on the calculated time-of-flight and the compared intensities.

The foregoing description has been presented for purposes of illustration and description. It is not exhaustive and does not limit embodiments of the invention to the precise forms disclosed. Modifications and variations are possible in light of the above teachings or may be acquired from the practicing embodiments consistent with the invention. For example, some of the described embodiments and figures pertain to specific numbers, orientations, and positions of apertures, light sensors, photodetectors, and electrodes, but in other embodiments, different numbers, orientations, shapes, and positions of these components may be used.

We claim:

1. A time-of-flight system comprising:
- a transmitter emitting a pulse of light;
- a lens-less detector having:
- a plurality of light sensors, each accepting light from any angle and detecting a different portion of the light pulse that passes through an aperture in the detector after being emitted from the transmitter and reflected off an object;
- a periphery having a plurality of non-intersecting slit apertures, at least two of which are oriented orthogonally to each other; and
- a calculation device coupled to the transmitter and the detector for calculating a time-of-flight of the light pulse and a position of the object relative to the detector based on the calculated time-of-flight and a calculated proportion of the portions of the reflected light pulse detected at the light sensors.

2. The system of claim **1**, wherein the detector includes two light sensors and the calculation device calculates the object position in two dimensions, a first of the two dimensions is obtained from the calculated proportion and a second of the two dimensions is obtained from the calculated time-of-flight.

3. The system of claim **1**, wherein the detector includes at least three light sensors and the calculation device calculates the object position in three dimensions, two of the dimensions are obtained from the calculated proportion of the portions of the reflected light pulse detected at the at least three sensors and a third of the dimensions is obtained from the calculated time-of-flight.

4. The system of claim **1**, wherein the light sensors each detect a different portion of the light pulse reflected off a plurality of objects.

5. The system of claim **4**, wherein the calculation device calculates a time-of-flight of the light pulse with respect to each of the objects based on peak currents generated at each light source over time and compares respective peak currents of different light sources to each other and the calculated time-of-flight for the respective object to calculate the position of the respective object.

6. The system of claim **1**, wherein the light sensors include a pair of photodetectors isolated from each other at a boundary between them, the boundary aligned with at least one of the plurality of slit apertures.

7. The system of claim **6**, wherein the boundary is aligned with the aperture when a center of the boundary is centered with a center of at least one of the plurality of slit apertures.

8. The system of claim **1**, wherein the sensors are photodetectors and the lens-less detector includes a measuring device calculating an angle of incident light from a proportion of the incident light detected at at least two of the photodetectors after passing through at least one of the plurality of slit apertures.

9. A time-of-flight system, comprising:
- a transmitter emitting a pulse of light;
- a detector having a plurality of light sensors, each detecting a different portion of the light pulse after being emitted from the transmitter and reflected off an object, the detector including:
  - a periphery having a plurality of slit apertures, at least two of which are oriented orthogonally to each other;
  - a substrate having a continuous epitaxial layer with a continuous surface receiving light passing through at least one of the plurality of slit apertures; and
  - a plurality of electrodes, each contacting the epitaxial layer to detect a quantity of the received light, wherein the plurality of electrodes includes two electrodes positioned at equal distances from at least one of the plurality of slit apertures and opposite each other; and
- a calculation device coupled to the transmitter and the detector for calculating a time-of-flight of the light pulse and a position of the object relative to the detector based

on the calculated time-of-flight and a calculated proportion of the portions of the reflected light pulse detected at the light sensors.

10. The system of claim **1**, the detector further comprising:

a substrate having an epitaxial layer receiving light passing through each of the slit apertures; and

a set of electrodes associated with each slit aperture, each electrode in each set arranged in the epitaxial layer to detect a quantity of the received light passing through the respective slit aperture, wherein the epitaxial layer has a continuous surface at least for each set of electrodes that encompasses the electrodes in each respective set of electrodes.

11. The system of claim **10**, wherein the epitaxial layer has a single continuous surface encompassing every electrode.

12. The system of claim **10**, wherein the epitaxial layer is germanium based.

13. A method comprising:

emitting a light pulse;

detecting different portions of the light pulse at each of a plurality of light sensors based on a first reflection and at least one subsequent reflection of the light pulse off an object passing through at least one of a plurality of slit apertures, wherein at least two of the plurality of non-intersecting slit apertures are oriented orthogonally to each other an aperture; calculating a time-of-flight of the light pulse;

comparing an intensity of at least two of the different portions to each other;

calculating a position of the object based on the calculated time-of-flight and the intensity comparing.

14. The method of claim **13**, further comprising:

calculating an angle of the reflected light pulse from the intensity comparing;

calculating the position of the object in a first dimension based on the calculated angle; and

calculating the position of the object in a second dimension based on the calculated time-of-flight.

15. The method of claim **13**, further comprising:

comparing the intensity of different portions of the light pulse detected at each of a first pair of light sensors to each other;

calculating a first angle of the reflected light pulse with respect to the first pair of light sensors from the first light sensor pair intensity comparing;

comparing the intensity of different portions of the light pulse detected at each of a second pair of light sensors to each other;

calculating a second angle of the reflected light pulse with respect to the second pair of light sensors from the second pair intensity comparing, the second pair of light sensors being non-parallel to the first pair;

calculating the position of the object in a first and a second dimension based on the calculated first and second angles of the reflected light pulse; and

calculating the position of the object in a third dimension based on the calculated time-of-flight.

16. The method of claim **13**, further comprising:

detecting the intensity of different portions of the reflected light pulse passing through at least one of the plurality of slit apertures at each of a plurality of electrodes in an epitaxial layer on a substrate, the epitaxial layer having a continuous surface encompassing each of the electrodes;

comparing the detected intensities of the light pulse at at least two of the electrodes to each other;

calculating the position of the object based on the calculated time-of-flight and the compared intensities.

17. The method of claim **16**, further comprising not focusing the reflected light pulse.

18. The method of claim **13**, further comprising:

detecting the intensity of different portions of the light pulse passing through at least one of the plurality of slit apertures at each of a plurality of photodetectors;

comparing the detected intensities of the light pulse at at least two of the photodetectors to each other; and

calculating the position of the object relative to the detector based on the calculated time-of-flight and the compared intensities.

19. The method of claim **13**, wherein a number of resolvable light pulses determines a number of measurable independent objects.

20. The method of claim **13**, wherein the detecting of the different portions of the light pulse includes calculating a centroid of the first reflection and the at least one subsequent reflection based on comparing currents at electrodes of each of the plurality of light sensors.

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